ECONOMIZER SYSTEM COST EFFECTIVENESS: ACCOUNTING FOR THE INFLUENCE OF VENTILATION RATE ON SICK LEAVE

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ABSTRACT
This study estimated the health, energy, and economic benefits of an economizer ventilation control system that increases outside air supply during mild weather to save energy. A model of the influence of ventilation rate on airborne transmission of respiratory illnesses was used to extend the limited data relating ventilation rate with illness and sick leave. An energy simulation model calculated ventilation rates and energy use versus time for an office building in Washington, D.C. with fixed minimum outdoor air supply rates, with and without an economiser. Sick leave rates were estimated with the disease transmission model. In the modelled 72-person office building, our analyses indicate that the economizer reduces energy costs by approximately $2000 and, in addition, reduces sick leave. The financial benefit of the decrease in sick leave is estimated to be between $6,000 and $16,000. This modelling suggests that economizers are much more cost effective than currently recognized.

INDEX TERMS
Economics, energy, infectious disease, ventilation rate, ventilation system

INTRODUCTION
The effects of ventilation rates (i.e., rates of outdoor air supply) on human responses has been reviewed by Seppänen at al. (1999) and Wargocki et al. (2001). These reviews indicate that the prevalence of some communicable respiratory diseases and of worker sick leave is decreased with higher ventilation rates. An economizer control system is an energy efficiency measure that increases ventilation rates during mild weather to reduce the need for mechanical cooling. Because economizers increase average ventilation rates, they should decrease respiratory illnesses and sick leave. The economic benefits of the decreases in sick leave have not normally been recognized; therefore, economizers may be underutilized. This paper provides a model for estimating how ventilation rates influence illness and sick leave, and another model to estimate how an economizer affects building energy use. The total financial benefits of the economizer are then calculated.

METHODS
A quantitative relationship between ventilation rate and sick leave was estimated using a model of airborne disease transmission fit to the data from several epidemiologic studies. We started with the Wells-Riley equation (Nardell et al. 1991) developed previously to estimate

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the effect of ventilation rates on airborne transmission of infectious respiratory diseases, assuming well-mixed indoor air

$$P = \frac{D}{s} = 1 - \exp\left[-\frac{ipqt}{Q}\right] \qquad (1)$$

where: P = proportion of new disease cases among the susceptible persons; D = number of new disease cases; s = number of susceptible persons; i = number of infectors; p = breathing rate; q = the rate at which an infector disseminates infectious particles; t = time that infectors and susceptibles share a confined space or ventilation system; Q = rate of supply of outdoor air. Rewriting equation (1) we obtain

$$P = \frac{D}{s} = 1 - \exp\left[(-\frac{ipqt}{V})\Big/(n_v)\right] \qquad (2)$$

where: V = indoor air volume; i/V = infectors per unit volume; $n_v = Q/V$ = ventilation rate. Equation 1 neglects the removal of infectious particles by filtration and by deposition on room surfaces, which are significant processes in removing airborne particles from room air. These removal processes can be expressed with effective removal rates per unit volume n_f and n_d , yielding the equation

$$P = \frac{D}{s} = 1 - \exp\left[(-\frac{ipqt}{V})\Big/(n_v + n_f + n_d)\right] \qquad (3)$$

where: n_f is the removal rate of infectious particles by filtration, equal to the product of the recirculation air flow rate and the filter efficiency; and n_d is the removal rate of particles due to deposition on room surfaces. We estimated n_f and n_d assuming the aerodynamic diameter of infectious particles is 1 μm (Gerone et. al 1966; Duguid 1946); however, the actual size distribution of these particles is poorly understood. The estimated value of n_f is 0.8 h^{-1}, based on a recirculation rate of 4 h^{-1} through the air handling system's filters typical of a commercial building in the U.S. and on a particle removal efficiency of 20% for 1 μm particles (assuming a filter with a mid-range ASHRAE dust spot filter efficiency rating of 40%). Based on the review of particle deposition rate data by Thatcher et al. (2001), we assumed that $n_d = 0.3\ h^{-1}$ for 1 μm particles.

In this equation the term $ipqt/V$ is the unknown. The value of this term will vary over time; however, effective time-average values can be estimated using the data from various epidemiologic studies that provide sufficient information to determine a lower and a higher reference ventilation rate (denoted $n_{v,low}$ and $n_{v,ref}$) and a relative risk (RR), which indicates the prevalence of the illness at the lower ventilation rate divided by the prevalence at the reference ventilation rate. For each study, we computed a value of $ipqt/V$ at the reference ventilation rate, denoted $i_{v,ref}\,pqt/V$, using the equation

$$RR = \left[1 - \exp\left[-\frac{\left(\left(\frac{i_{v,low}\,pqt}{V}\right)\right)}{(n_{v,low} + n_f + n_d)}\right]\right]\Bigg/\left[1 - \exp\left[-\frac{\left(\frac{i_{v,ref}\,pqt}{V}\right)}{(n_{v,ref} + n_f + n_d)}\right]\right] \qquad (4)$$

The value of " i", which is the number of infectious people in the building, should, in general, increase as the ventilation rate decreases. If there were no introduction into the building of infectious individuals who became infected outside of the building, $i_{v,low}$ would equal the product of RR and $i_{v,ref}$. If all individuals who became ill due to exposures inside the building were instantaneously removed and, thus, unable to infect others, and infections of building occupants were due only to the introduction of infectious individuals who became infected outside of the building, $i_{v,low}$ would equal $i_{v,ref}$. In real buildings, the situation is between these extremes. As a first approximation, we assume that half of the infectious individuals introduced in the building became infected outside of the building and half became infected inside the building; thus, $i_{v,low} = i_{v,ref}(1 + RR)/2$.

Table 1 provides the values of $n_{v,low}$, $n_{v,ref}$ and RR obtained from published studies (with a few assumptions required). Once the value of $i_{v,ref}\, pqt/V$ was known, equation 4 was used to calculate RR for a range of ventilation rates between 0 and 4 h^{-1}, with the reference ventilation rate being $n_{v,ref}$. Finally, all values of RR were normalized by the value of RR computed for no ventilation. For comparison to the disease transmission model represented by equation 4, we also used a much simpler model in which the disease prevalence is proportional to reciprocal of the total infectious particle removal rate

$$P \propto 1/\left(n_v + n_f + n_d\right) \qquad (5)$$

This model is consistent with the assumption that the disease prevalence in the building is proportional to the indoor concentration of infectious particles.

To estimate the economic costs of different disease prevalences, we assumed that short term sick leave is proportional to the prevalence of respiratory illness. With hourly predictions of ventilation rates (described below), a seasonal average value of P was calculated. From the data from Milton et al. (2000), we assumed that the baseline short-term sick leave rate was 2% with a ventilation rate of 0.45 h^{-1}, enabling a calculation of the annual average sick leave rate. Finally, a day of sick leave was valued at $200, based on annual total salary plus benefits of $50,000 and 250 work days per year.

Table 1. Data used in equation 4 and resulting value of $i_{v,ref}\, pqt/V$.

Reference	$n_{v,low}$ **(h^{-1})**	$n_{v,ref}$ **(h^{-1})**	**RR**	$I_{v,ref}\, pqt/V$
Milton et al. (2000), short term sick leave	0.43	0.86	1.5	0.453
Brundage et al. (1988), illness all years	0.15	1.0	1.5	1.651
Brundage et al. (1988), illness 1983 data	0.15	1.0	1.9	0.841
Drinka et al. 1996, illness	1.6	4.0	2.2	1.870
Drinka et al. (1996), influenza	1.6	4.0	4.7	0.358
Hoge et al. (1994), pneumonia	0.68	1.0	2.0	-0.49

The disease transmission models were applied to hourly predictions of outside air ventilation rates in a hypothetical moderate-size two-story office building located in Washington, DC. The ventilation rate predictions and associated HVAC energy use predictions were made with the widely-used DOE-2 program. Key building characteristics include: 2000 m^2 floor area; 5669 m^3 conditioned volume; 72 occupants; an internal heat generation of 20 W m^{-2} from lights and equipment; and an air infiltration rate of 0.3 h^{-1}. The building had a variable air volume HVAC system; thus, the supply flow rate was modulated to control indoor temperature, with a design maximum flow rate of 4.1 L s^{-1} per square meter of floor area. Simulations were performed assuming minimum outside air supply rates by the HVAC system during occupancy of 10, 15, and 20 L s^{-1} per person, with and without a temperature-based economizer control system that increased the ventilation rate above the minimum whenever providing increased outside air was more economical than mechanical cooling. The HVAC system operated between 06:00 and 21:00. The assumed percent of total occupancy versus time of day was as follows: 25% at 08:00; 75% at 09:00; 95% at 11:00 – 12:00; 75% at 13:00; 95% at 14:00 – 16:00; 75% at 17:00; 50% at 18:00; 35% at 19:00, 10% at 20:00, and 5% at 21:00. Annual energy costs were calculated using prices <www.eia.doe.gov> during 2001 in Washington, D.C. for electricity and natural gas of $0.076 per kWh and $10.87 per GJ, respectively.

RESULTS

The right hand column of Table 1 provides the calculated values of $i_{v,ref}\,pqt/V$. Figure 1 plots the calculated values of illness or short-term sick leave versus ventilation rate, normalized by the illness or sick leave rate predicted with no ventilation. All predictions show the expected decrease in illness over time; however, the rate of decrease varies dramatically for low ventilation rates, with the prediction based on the data of Drinka et al. (1996) appearing as an outlier. The simple particle concentration model (Equation 5) provides a mid-range prediction.

Application of the disease model (Equation 4) to the results of Hoge et al. (1994) yielded a negative value of $i_{v,ref}\,pqt/V$, which is physically impossible. Application of the model to the influenza data of Drinka et al. (1996) yielded a positive value of $i_{v,ref}\,pqt/V$; however, the subsequent calculations yielded some negative relative risks with ventilation rates near zero, which is also impossible. The disease model cannot account for the high reported relative risks and associated ventilation rates in these studies.

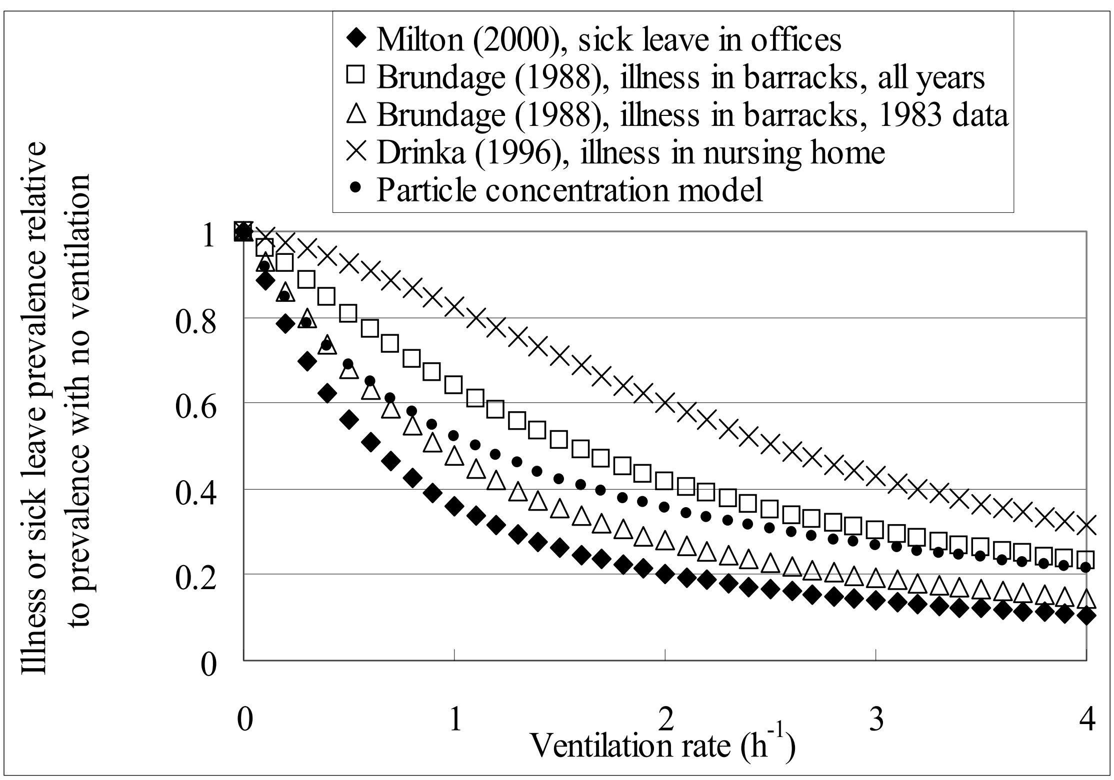

Figure 1. Predicted trends in illness or sick leave versus ventilation rate

The predicted HVAC energy use, ventilation rate, days of sick leave for the workforce, and the associated costs of energy and sick leave are provided in Table 2. The upper and lower estimates of sick leave were based on the curves in Figure 1 for Milton and Drinka, respectively. The economizer system reduces annual HVAC energy costs by approximately $2,000. The estimated savings due to reduced sick leave with the economizer ranges from $6,000 to $16,000.

Table 2. Predicted annual HVAC energy use, ventilation rates, and sick leave

Min Vent*	**Vent Rate#**	**Econo-mizer**	**Annual HVAC Energy**			**Lower and Upper Estimate of Annual Sick Leave**			
L s^{-1}	h^{-1}	Y or N	Elec. MWh	Gas GJ	Total $US	Lower days	Lower $	Upper days	Upper $
10	0.74	N	298	674	30000	264	53000	340	68000
10	1.46	Y	269	706	28000	186	37000	274	55000
10	**Savings from economizer**				**1900**	**78**	**16000**	**66**	**13000**
15	0.96	N	303	699	31000	216	43000	321	64000
15	1.56	Y	272	723	29000	162	32000	267	53000
15	**Savings from economizer**				**2100**	**54**	**11000**	**54**	**11000**
20	1.18	N	308	734	31000	180	36000	298	60000
20	1.67	Y	276	752	29000	150	30000	259	52000
20	**Savings from economizer**				**2200**	**30**	**6000**	**39**	**7700**

*per person #yearly average Note: Numbers may not add precisely due to rounding

DISCUSSION

There are many sources of uncertainty in the model used to relate ventilation rates to sick leave. Most important is the limited empirical data available to calibrate and evaluate the model. In addition, there are uncertainties in the size, filtration rate, and deposition rate of infectious particles in typical buildings. Also, the natural loss of viability of airborne infectious particles has not been accounted for in the model due to a lack of information on the survival times of the airborne virus and bacteria that cause respiratory diseases. If suitable information were available, viability loss could be incorporated in the model as filtration and depositional losses were incorporated. The rate at which an infector disseminates infectious particles will likely vary among illnesses. The susceptibility to infection will vary with the age, health status, and immunizations of the occupants of the building. It is likely that these and other factors, including different amounts of time spent in different types of buildings, partially explain the different curves shown in Figure 1.

The disease transmission model represented by Equations 1-4 is theoretically superior to the model represented by equation 5. However, given the limited empirical data available to calibrate and evaluate the complex model, and the wide range of associated predictions, the complex model may not, at present, be any more useful than the simple model represented by Equation 5.

Despite these large sources of uncertainty, a rough accounting of the influence of ventilation rates on sick leave may lead to better decisions about building design and operation than totally neglecting this issue. Clearly, individual decision makers will have to decide whether or not to consider uncertain but potentially large benefits. When we do account for our range of estimates of the reduced sick leave from an economizer system, the economizer becomes much more attractive than it appears based on energy savings alone. The estimated financial value of the sick leave reduction from economizer use is three to eight times as large as the estimated energy cost savings. In the U.S., minimum ventilation requirements for offices are generally 10 L s^{-1} per person; thus, the most relevant estimates of the related benefits from economizer use in this building are $1,900 for energy and $13,000 to $16,000 for sick leave reductions. Even if the sick leave savings are a factor of ten smaller than predicted, they would still be comparable to the energy savings. The influence of economizer use on illness would need to be extremely small to make the related savings negligible. There is one recent study (Myatt et al. 2002) that failed to find an effect of ventilation rate on sick leave; however, the majority of the limited evidence available indicates that ventilation rate does affect sick leave. It is clear that more research is warranted to elucidate this issue.

The data in Table 2 enable a comparison of economizer use to higher values of ventilation rates in HVAC systems without economizers. Based on the estimates in this paper, adding an economizer to a HVAC system with a minimum ventilation rate of 10 L s^{-1} per person (which saves energy), would bring about larger sick-leave-related savings than increasing the minimum ventilation rate to 15 L s^{-1} per person. When both energy and sick leave-related savings are considered, the economizer option with a 10 L s^{-1} per person minimum ventilation rate is predicted to be more economical than a fixed 20 L s^{-1} minimum ventilation rate. However, we caution the reader that other possible impacts of ventilation rates on health or productivity or equipment costs have not been considered.

Currently economizers are often not considered cost effective for smaller HVAC systems. Economizer performance failures are also common. This modeling suggests that properly functioning economizers may be much more cost effective than currently recognized. The benefits of other energy efficiency measures that increase ventilation rates would also be higher than currently recognized. Examples include evaporative air conditioning systems for dry climates that use 100% outside air, and the use of heat recovery systems together with higher ventilation rates. Also, if the observed reductions of respiratory illness with increased ventilation are a consequence of increased removal infectious particles, the same benefits might be achieved by improving filter efficiencies, which can have a negligible impact on HVAC energy use (Fisk et al 2002).

CONCLUSIONS

- The majority of existing literature indicates that increasing ventilation rates will decrease respiratory illness and associated sick leave.
- A disease transmission model, calibrated with empirical data, has been used to estimate how ventilation rates affect sick leave; however, the model predictions have a high level of uncertainty.
- Financial benefits of the use of an economizer system were estimated considering both the energy savings and the value of reductions in sick leave. The estimated financial

value of the sick leave reduction from economizer use is three to eight times as large as the estimated energy cost savings. Thus, economizers may be much more cost effective than currently recognized.

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